Saccadic and perceptual performance in visual search tasks. II. Letter discrimination

Richard F. Murray

MS 262-2, NASA Ames Research Center, Moffett Field, California 94035-1000, and Department of Psychology, University of Toronto, Toronto, Ontario, Canada, M5S 3G3

Brent R. Beutter

MS 262-2, NASA Ames Research Center, Moffett Field, California 94035-1000

Miguel P. Eckstein

Department of Psychology, University of California at Santa Barbara, Santa Barbara, California 93106-9660

Leland S. Stone

MS 262-2, NASA Ames Research Center, Moffett Field, California 94035-1000

Can the oculomotor system use shape cues to guide search saccades? Observers searched for target letters (D, U, or X) among distractors (the letter O in the discrimination task and blank locations in the detection task) in Gaussian white noise. We measured the accuracy of first saccadic responses on each trial and perceptual (i.e., button-press) responses in separate trials with the stimulus duration chosen so that the saccadic and perceptual processing times were matched. We calculated the relative efficiency of saccadic decisions compared with perceptual decisions, $\eta_{\mathrm{rel}} = (d'_{\mathrm{sac}}/d'_{\mathrm{per}})^2$. Relative efficiency was low but consistently greater than zero in discrimination tasks ($15\% \pm 6\%$) and high in detection tasks ($60\% \pm 10\%$). We conclude that the saccadic targeting system can use shape cues, but less efficiently than the perceptual system can. © 2003 Optical Society of America

OCIS codes: 330.2210, 330.4060, 330.5000, 330.5510, 330.6100, 330.7310.

1. INTRODUCTION

Human observers make frequent saccades, both when passively surveying a scene and when actively searching for a known target, but it is not well understood how observers choose the locations to which they make saccades. Here we investigate how well observers can use the *shape* of a known target to guide saccades during visual search.

A. Absolute and Relative Efficiency of Saccadic Responses

Previous studies of whether shape cues can guide saccades have reached differing conclusions. Some have concluded that shape cues have a strong influence on saccades,[1–3] while others have concluded that they have little or none.[4–6] One way out of this impasse is suggested by the finding that saccades are guided more strongly by shape cues when target and distractor shapes are highly discriminable.[2,4] In any meaningful attempt to evaluate saccadic performance in a given task (or perceptual performance, for that matter), we must take account of how much task-relevant information the stimulus provides to the observer; i.e., we must take account of the intrinsic difficulty of the task. This has not often been done in studies of saccadic targeting. For instance,

Williams[5] found that saccades were strongly guided by color cues and not by shape cues, but he gave few details as to what color or shape cues his stimuli provided. In the limit, if the color cues were salient and informative and if the shape cues were faint and unreliable, then such results would say more about the stimuli than about saccadic targeting. The same principle applies when differences between various cues are less extreme: To properly evaluate how well an observer uses a cue to perform a task, we must somehow take into account how much task-relevant information the cue provides.

Eckstein *et al.*[7] and Beutter *et al.*[8] investigated how well observers can use *contrast* cues to guide saccades during visual search. They regarded observers' first saccade on each trial of a visual search task as a kind of saccadic response, which indicated the oculomotor system's best initial guess as to where the target was located. They considered the first saccade to be correct if it was directed toward the correct target location, and using this definition, they measured the proportion of correct first saccadic responses in disk detection and contrast discrimination tasks. To take account of the amount of information provided by the contrast cues in their tasks, they compared the accuracy of observers' first saccades with two reference standards. First, they compared sac-

cadic performance with the ideal observer's performance by calculating the *absolute* efficiency of saccades:

$$\eta_{abs} = (d'_{sac}/d'_{ideal})^2. \qquad (1)$$

Here d'_{sac} is the observer's saccadic performance, and d'_{ideal} is the ideal observer's performance, both measured in terms of d'.[9] Second, they compared saccadic performance with the same human observer's perceptual performance (i.e., button-press performance) in the same task by calculating the *relative* efficiency of saccades:

$$\eta_{rel} = (d'_{sac}/d'_{per})^2. \qquad (2)$$

Here d'_{sac} is again the observer's saccadic performance, and d'_{per} is the observer's perceptual performance.

These two comparisons are informative in different ways. By comparing saccadic performance with ideal performance, we learn how efficiently the saccadic system uses all the information provided by the stimulus, and we answer the question of how well the saccadic system performs on an absolute scale. However, human performance is invariably worse than ideal performance (often much worse), and from a comparison of saccadic performance with ideal performance, it may be difficult to gain a sense of how well the saccadic system actually performs. By comparing saccadic performance with perceptual performance, we learn how well the saccadic system performs compared with a more familiar system that shares many early performance-limiting constraints with the saccadic system, such as optical blur and retinal sampling.[10] For instance, learning that saccades are approximately as accurate as perceptual responses in a given task may be more helpful than learning that they have an absolute efficiency of 25%.

In the present experiments, we investigated how well saccades are guided by shape cues during visual search for letters. To take account of the intrinsic difficulty of our search tasks, we followed the approach of Eckstein *et al.*[7] and Beutter *et al.*:[8] We compared saccadic performance with ideal performance, and with perceptual performance in the same task with the stimulus duration approximately matched to the time required to make a saccadic decision (~150 ms).

B. Shape Cues and Contrast Cues
Another important concern when evaluating how well observers use a given cue to perform a task is to ensure that the stimulus does not provide alternative cues that the observer could also use to perform the task. In previous studies of saccadic targeting, shape cues have almost always been confounded with contrast cues. Most studies have equated the peak Weber contrast of targets and distractors, but there are many other ways of measuring perceptual salience,[11–13] and in general it is difficult to know which measure, if any, eliminates all contrast cues in a given task. This is a serious confound because saccades can be guided very effectively by contrast cues.[7,8]

To evaluate how well observers use shape information to guide saccades and to be certain that observers were not also using contrast cues, in experiment 2 we compared saccadic and perceptual performance during visual search for a target letter among distractor letters, and we independently randomized the contrasts of the target and the distractors on every trial. Under these conditions, even an observer who made statistically optimal use of simple contrast cues would perform very poorly. If saccadic accuracy was much better than chance even under these conditions, we could be certain that the saccadic system was using shape cues to guide saccades, and not contrast cues.

C. Stimulus Information Mediating Saccadic and Perceptual Responses
If saccadic and perceptual responses are determined by the same computations on the stimulus, then saccadic and perceptual performance should be affected similarly by a wide range of task and stimulus manipulations. This would suggest that saccadic and perceptual performance might be limited by the same neural mechanisms. To investigate this possibility, we compared saccadic and perceptual performance in three ways: first, in shape discrimination versus contrast discrimination tasks; second, in letter discrimination versus letter detection tasks; and third, as a function of signal contrast.

D. Overview
In all three of the following experiments, we measured saccadic performance during visual search for a target letter in white Gaussian noise, and in separate trials we measured perceptual performance in the same task, with the stimulus duration matched to the time required to make a saccadic decision. In the first experiment, the goal was to compare saccadic and perceptual performance over a range of signal contrasts, and to do this, we measured performance at four signal contrasts chosen to produce a range of perceptual performance from near chance to nearly 100% correct. In the second experiment, we independently randomized the contrast of the target and distractor letters to rule out the possibility that observers were making saccades based on simple contrast cues rather than on shape differences between the target and the distractors. In the final experiment, we measured performance in a detection task in which observers searched for a target letter without distractors.

2. EXPERIMENT 1: LETTER DISCRIMINATION

A. Methods
1. Participants
One author (RFM) and three other observers participated. All had normal Snellen acuity, all were experienced at psychophysical tasks, and, other than the author, none was aware of the purpose of the experiment.

2. Stimuli
Figure 1(a) shows a typical stimulus. Ten squares with sides of length 2.4 degrees of visual angle (deg) were evenly spaced around a circle of radius 5.9 deg, centered on a fixation cross. The squares and the fixation cross were drawn with gray lines that were 0.12 deg thick and

(a)   **(b)**   **(c)**
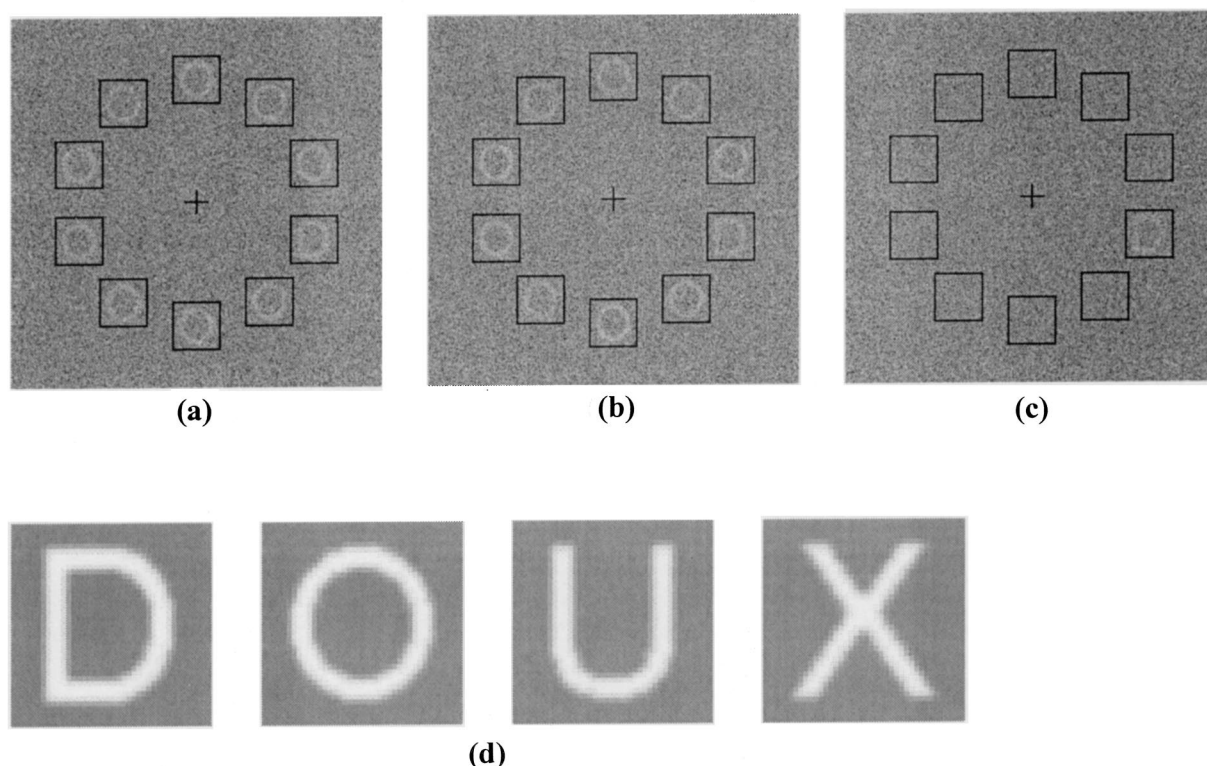

(d)

Fig. 1.   Typical stimuli from (a) experiment 1, (b) experiment 2, and (c) experiment 3.   In (c), the contrast of the target has been increased to 15% to make the figure clearer.   Image (d) shows closeups of the target and distractor letters.

had a luminance of 0.40 cd/m^2, on a gray background of luminance 30 cd/m^2.   One of three target letters (D, U, or X) appeared in one of the squares, and the letter O appeared in the other nine squares.   The letter images were 40×40 pixels, created by blurring 41-pixel Arial-font letters with a Gaussian kernel of standard deviation 0.75 pixel in order to smooth jagged edges [Fig. 1(d)].   The entire 18-deg $\times$ 18-deg stimulus was covered by a square of Gaussian white noise of root-mean-square contrast 16% (power spectral density 8.9×10^{-5} deg^2).   The noise was generated by adding a random luminance offset to each pixel.

On each trial, the peak Weber contrast [defined as $c_W = (L - L_{bg})/L_{bg}$, where L is the luminance of the point of interest and L_{bg} is the background luminance] of the target and distractor letters was randomly set to one of four values chosen to span the observers' psychometric functions, based on performance in practice sessions. That is, the contrasts of the target and the distractors were the same on any given trial but varied from trial to trial.   Observers found some target letters more difficult to locate than others, so we used different contrasts for each target letter task.   For observers AEK, KRB, and RFM, the contrasts were as follows: target D, contrasts 8%, 12%, 16%, and 20%; target U, contrasts 6%, 8%, 12%, and 16%; and target X, contrasts 4%, 6%, 8%, and 12%. For observer STS, the contrasts were the following: target D, contrasts 10%, 15%, 20%, and 25%; target U, contrasts 7%, 10%, 15%, and 20%; and target X, contrasts 5%, 7%, 10%, and 15%.

Observers viewed the stimuli binocularly on a Philips Brilliance 21A monitor (pixel size 0.59 mm, resolution 640×480, refresh rate 60 Hz) at a viewing distance of 0.57 m.

3. Eye-Tracking Methods
During all trials, the position of the left eye was measured by using an infrared video-based eye tracker (ISCAN Inc., NASA prototype) sampling at 240 Hz and synchronized with the 60-Hz screen refresh of the monitor.   Head movements were minimized by using a bite bar.   The eye tracker was calibrated by having observers sequentially fixate nine crosses arranged in a 12 deg $\times$ 12 deg grid at the beginning and the end of each block of 100 trials. The eye position at the beginning of each trial, when observers looked at the fixation cross, was used to correct for small head movements.   The eye-tracker precision was generally better than 0.15 deg, as estimated from the standard deviation of eye position during a fixation.   We detected saccades by low-pass filtering the eye position signal (-3 dB cutoff at 42 Hz) and marking a saccade when eye velocity exceeded a threshold.   The saccade's end point was defined to be the mean eye position during the subsequent fixation.   See Beutter *et al.*[8,14] for more information on our eye-tracking and saccade detection methods.

4. Procedure
Each observer participated in 13 or 14 1-h sessions, of which the first two were discarded as practice sessions. Each session consisted of six 100-trial blocks: one eye-

movement (EM) block and one fixation (FIX) block for each of the three target letters (D, U, and X). Observers searched for the same target letter on all trials within a given block. The six blocks were run in random order. Observers were told to locate the target letter and to indicate its location by using the buttons on a mouse, as described below.

At the beginning of each EM trial, the observer foveated the fixation cross and clicked a mouse button to start the trial. After a pause of 500 ms, during which time the fixation cross remained on the screen, the stimulus appeared [Fig. 1(a)]. The observer searched for the target letter, typically making several saccades, and clicked the mouse to indicate that he had found the target. After this mouse click, or after 6 s, whichever came first, the stimulus was replaced by a 200-ms white-noise postmask, of root-mean-square contrast 67% (power spectral density 1.6×10^{-3} deg^2). Immediately after the postmask, a response screen was shown, containing ten empty squares in the same locations as the stimulus squares, with an arrow that the observer could rotate in either direction by clicking buttons on the mouse, to point at any of the ten squares. The observer rotated the arrow to point at the location where he thought the target letter had appeared and then pressed another mouse button to indicate that this location was his response. The observer was not given feedback as to whether the response was correct. In Subsection 2.B, we briefly discuss the accuracy of button-press responses on EM trials, but ultimately they were of secondary importance, because we were mainly interested in the accuracy of observers' first saccadic responses on EM trials. We assigned the first saccade on each EM trial to whichever of the ten stimulus locations was nearest to the saccade's end point. We ignored small initial saccades: We considered the first saccade on each trial to be the first that ended more than 1 deg from the fixation cross. We discarded trials on which the first saccade began less than 100 ms after stimulus onset or landed more than 9 deg from fixation. Approximately 2% of EM trials were rejected by these criteria.

Each FIX trial also began with the observer foveating the fixation cross and clicking a mouse button to proceed. On FIX trials, the observer maintained fixation for the entire trial. The stimulus was displayed for a much shorter duration, chosen to match the processing time required by each observer to select the target location for the first saccade on EM trials. Specifically, the stimulus duration on FIX trials was set to each observer's median saccadic latency over the EM trials of the two practice sessions, minus the 90 ms required to program a saccadic eye movement,[15] rounded to the nearest display time possible on the 60-Hz monitor. The stimulus duration was 150 ms for observers AEK, RFM, and STS and 250 ms for KRB. As on EM trials, the stimulus was followed by a high-contrast postmask and a response screen on which the observer rotated an arrow to indicate his response. We monitored eye movements on FIX trials in order to discard trials where the observer's eye position deviated by more than 1 deg from the fixation cross while the stimulus was shown, but this never happened, as the stimulus duration was shorter than the saccadic latency.

B. Results

1. Saccadic and Perceptual Decision Accuracy

The main goal of this study was to measure human saccadic performance during visual search for a target letter among distractor letters and to compare saccadic performance with perceptual performance under matched conditions. Figure 2 shows each observer's oculometric and psychometric functions, plotted as proportion correct versus signal contrast. The oculometric functions (left column) show the accuracy of observers' first saccades on EM trials, and the psychometric functions (right column) show the accuracy of observers' perceptual (i.e., button-press) responses on FIX trials. We will discuss the fitted curves in Subsection 2.B.4. The figure shows the main findings of this experiment very clearly: First, saccadic performance was better than chance (10% correct), meaning that within 200 ms of stimulus onset, shape cues were available to guide saccades; and second, saccadic performance was markedly worse than perceptual performance, as shown by the fact that proportion correct for saccadic responses for each target letter at each signal contrast
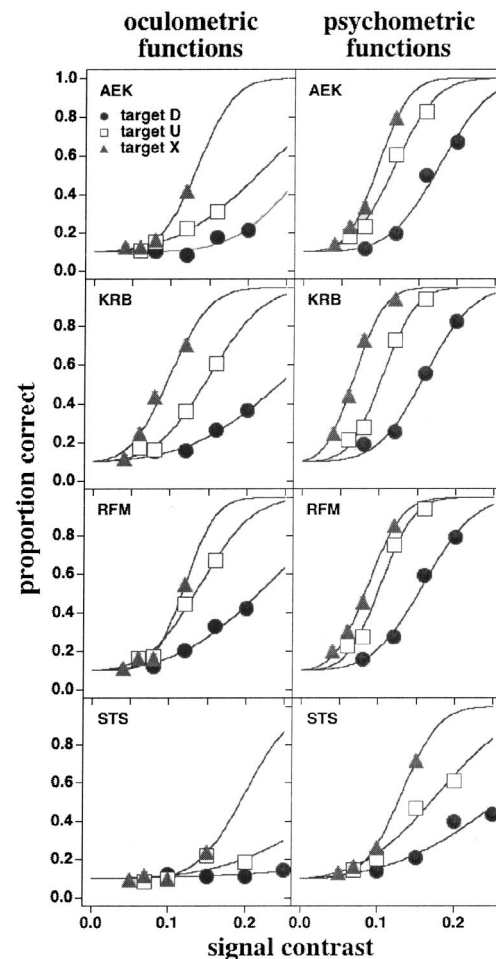

Fig. 2. Oculometric and psychometric functions from experiment 1, plotted as proportion correct versus signal contrast. The error bars show standard errors and are often smaller than the data points. The curves show maximum-likelihood fits of two-parameter functions derived from Eckstein *et al.*'s[7] efficiency-and-uncertainty model. Table 1 below reports the fitted parameters.
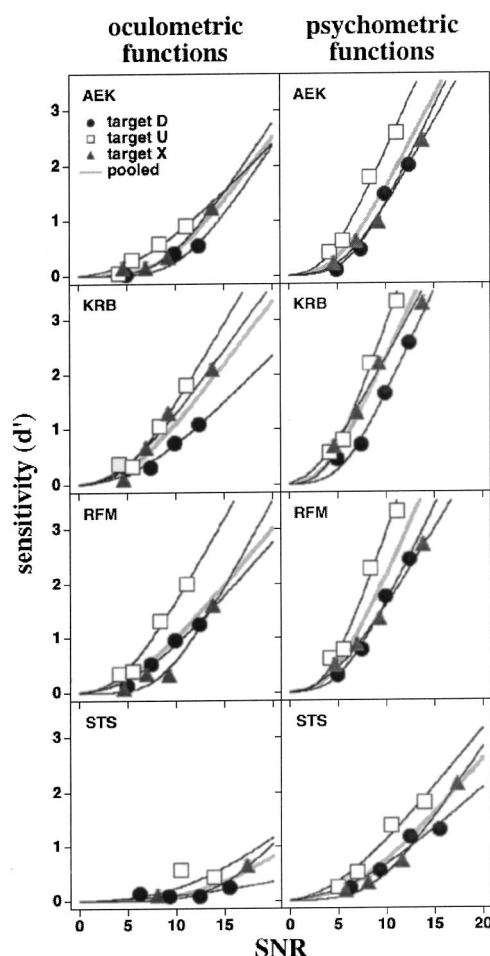
Fig. 3. Oculometric and psychometric functions from experiment 1. These are the same data as those shown in Fig. 2, replotted as human observers' d' versus ideal observer's d' (which we call the SNR). The thin black curves show individual maximum-likelihood fits of two-parameter functions derived from Eckstein *et al.*'s[7] efficiency-and-uncertainty model. The thick gray curves show simultaneous fits of the same type of function to performance in all three letter tasks. Table 1 below reports the fitted parameters.

was generally much lower than the corresponding proportion correct for perceptual responses.[16]

A plot of proportion correct versus signal contrast helps to give an intuition as to how well observers performed with various stimuli, but it is also informative to plot the human observers' saccadic and perceptual d' versus the ideal observer's d'. It is useful to plot performance in terms of d', because relative efficiency is the squared ratio of saccadic and perceptual d', whereas the difference or the ratio of two proportions correct has no theoretical significance.[7] It is useful to plot human performance as a function of the ideal observer's performance, because ideal performance indicates the intrinsic difficulty of a task, whereas signal contrast by itself tells us nothing about how much task-relevant information a stimulus provides to the observer. For instance, Fig. 2 shows that observers performed best with target letter X, worse with U, and worst with D, which suggests that much of the performance difference across target letter tasks was simply due to the difference in how similar the target letters

were to the distractor letter, which was always O. Plotting human performance as a function of ideal performance takes account of such differences in intrinsic task difficulty and shows whether there truly are differences in how efficiently observers use stimuli in different tasks.

Figure 3 replots the oculometric and psychometric functions as the human observers' d' versus the ideal observer's d'.[17–19] [Sometimes, as on the x axis of this plot, we call the ideal observer's d' the task's signal-to-noise ratio (SNR), because the ideal observer's d' is defined as the SNR available to an observer who uses the stimulus as efficiently as possible.] First, note that in Fig. 3 both the oculometric and psychometric functions from the three target letter tasks overlap much more than in Fig. 2, confirming that much of the performance difference across letter tasks was due to the difference in the intrinsic difficulty of the tasks. However, the functions do not overlap entirely, indicating a genuine difference in how efficiently observers used the stimuli in the three letter tasks. Second, note that both saccadic and perceptual performance were much worse than ideal performance. This comparison is easy to make in Fig. 3, as the ideal observer's d' is simply the SNR, i.e., the units of the x axis. A convenient way of comparing human and ideal performance is by calculating absolute efficiency, defined as $\eta_{abs} = (d'/d'_{ideal})^2$. Over all observers, target letters, and SNRs, saccadic absolute efficiency covered a range of 0%–3% and had a mean of 0.56% $\pm$ 0.11%, and perceptual absolute efficiency covered a range of 0%–9% and had a mean of 2.38% $\pm$ 0.33%. These values of perceptual absolute efficiency are lower than those reported in some previous studies of letter identification, but the discrepancy can be explained by differences in stimuli and tasks. For example, Solomon and Pelli[20] reported absolute efficiencies of approximately 10%, but their stimuli were viewed foveally and were bandpass filtered, and both of these factors tend to increase efficiency, so the fourfold difference between our measurements of efficiency and theirs is not surprising.

2. Relative Efficiency
As we discussed in Section 1, it is also informative to compare saccadic performance with perceptual performance. To make this comparison, we calculated the relative efficiency of the first saccade on EM trials with respect to perceptual decisions on FIX trials, defined as $\eta_{rel} = (d'_{sac}/d'_{per})^2$. Figure 4 shows the relative efficiency of each observer's first saccadic decisions at each SNR, calculated from the oculometric and psychometric data in Fig. 3. Mean relative efficiency, averaged across target letters and signal contrasts, was as follows: observer AEK, 11.1% $\pm$ 1.3%; KRB, 23.8% $\pm$ 1.6%; RFM, 25.0% $\pm$ 1.7%; and STS, 1.5% $\pm$ 0.7%. The error values are standard errors, obtained by assuming Bernoulli variability in observers' responses, and propagating errors.[21] Although saccadic performance was better than chance, each observer's relative efficiency was much less than 100%, meaning that observers used the stimuli much less efficiently when making saccadic decisions than when making perceptual decisions. We emphasize that relative efficiency compares saccadic performance on EM trials with perceptual performance on FIX trials and that
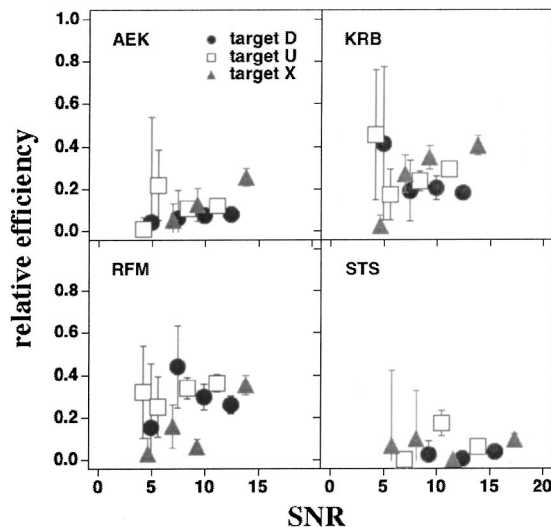
Fig. 4. Efficiency of first saccades on EM trials of experiment 1 relative to perceptual responses on FIX trials. Estimates of relative efficiency at low contrasts are ratios of two noisy, near-zero numbers and so are extremely noisy. The error bars show standard errors. Points with standard errors larger than 0.5 have been omitted from the plots.

the stimulus duration on FIX trials was approximately equal to the time that the observer took to make saccadic decisions on EM trials. Thus saccadic and perceptual decisions were based on approximately equally informative stimuli, and yet saccadic performance was consistently worse than perceptual performance.

Finally, with just four observers, it is difficult to interpret individual differences with any confidence. However, perhaps it is worth noting that of the two observers with the highest relative saccadic efficiency, one (KRB) had an unusually long saccadic latency, and the other (RFM) was an author and so knew that saccadic accuracy was being monitored.

3. Effect of Task Difficulty
One of our goals in this study was to see whether saccadic and perceptual performance were affected similarly by various task manipulations. To see whether saccadic and perceptual performance depended similarly on task difficulty, we examined relative efficiency as a function of SNR. Within-subject analyses of covariance (ANCOVAs) showed significant effects of SNR on relative efficiency for all observers [$F(2, 8) \geq 9.33, p < 0.02$]. All observers had higher relative efficiency at higher SNRs: Observer AEK's maximum-likelihood regression slope was 2% efficiency per unit SNR, KRB's slope was 3%, RFM's was 3%, and STS's was 1%. The SNRs covered a range of approximately 4–12, so, on average, relative efficiency increased by approximately 18% over the range of SNRs studied. This is a large effect, given that mean relative efficiency across observers was only 15%. Thus saccadic and perceptual performance did *not* show a similar dependence on SNR: Not only was saccadic performance generally worse than perceptual performance, but it was differentially worse at low SNRs. The ANCOVAs also showed a significant effect of target letter on relative efficiency for

observers AEK, KRB, and RFM [$F(2, 8) \geq 9.33, p < 0.02$]. The effect of target letter was idiosyncratic, with different observers showing higher relative efficiency with different target letters.

4. Model Fits
The curves that we fitted to the psychometric and oculometric functions in Figs. 2 and 3 are based on a two-parameter model of target localization that has been developed within signal detection theory.[22] The model describes an observer's performance in terms of two parameters: (1) a slope parameter α that measures the steepness of the psychometric function and indicates how well the observer estimates the likelihood of the target having appeared at each stimulus location and (2) the intrinsic uncertainty parameter U that indicates the number of irrelevant stimulus locations that the observer monitors (i.e., locations where the target could never appear). Table 1 reports the fits of the parameters α and U to the oculometric and psychometric functions in Figs. 2 and 3.

To see whether the difference between saccadic and perceptual performance was due to a difference in how well observers estimated the likelihood of the target having appeared at each stimulus location or due to a difference in intrinsic uncertainty, we compared the parameters α and U of the fitted oculometric and psychometric functions for each observer in each letter task. These parameters had non-Gaussian distributions, so instead of using the means and the standard errors of the parameters in t tests, we assumed Bernoulli variability in observers' responses and compared the parameters by nonparametric bootstrapping.[23] The slope parameter α was generally lower for saccadic responses than for perceptual responses ($p < 0.01$), with the following exceptions: Saccadic and perceptual values of α were not significantly different ($p > 0.05$) for observers AEK or RFM in the target X task or for STS in the target D and U tasks. Uncertainty was not significantly different ($p > 0.05$) for saccadic and perceptual responses, with one exception: Observer RFM had higher uncertainty for saccades in the target X task ($p < 0.01$). The significant differences in the slope parameters suggest that the perceptual system either uses templates that are better matched to the relevant stimulus information than the saccadic system's templates or has less internal noise than the saccadic system.[22]

The fitted values of α and U were similar across target letters for each observer, so we also made pooled fits, fitting a single function to each observer's saccadic performance in all three letter tasks and a single function to each observer's perceptual performance in all three letter tasks. These fits are shown in Fig. 3 as thick gray curves, and the fitted parameters are reported in Table 1. Clearly there were differences in the oculometric and psychometric functions across letter tasks, but nevertheless the pooled fits gave a reasonably good description of the data because the oculometric and psychometric functions from the three target letter tasks mostly overlapped when plotted as a function of SNR. We compared the parameters α and U for each observer's pooled oculometric and psychometric functions, and the results were largely

Table 1.   Parameters of Psychometric Functions in Experiment 1[a]

Observer Response	Parameter	Target D		Target U		Target X		Pooled	
AEK									
saccade	α	0.24	(0.11, 0.27)	0.17	(0.10, 0.26)	0.24	(0.18, 0.29)	0.22	(0.18, 0.28)
	U	3000	(18, ∞)	14	(1, 280)	590	(43, ∞)	311	(62, ∞)
percept	α	0.33	(0.28, 0.39)	0.36	(0.32, 0.41)	0.29	(0.26, 0.33)	0.31	(0.29, 0.34)
	U	398	(70, 5200)	40	(14, 181)	100	(31, 523)	65	(32, 186)
KRB									
saccade	α	0.17	(0.11, 0.25)	0.28	(0.24, 0.34)	0.23	(0.19, 0.27)	0.22	(0.20, 0.25)
	U	16	(2, 332)	37	(10, 279)	14	(4, 50)	19	(9, 52)
percept	α	0.35	(0.31, 0.40)	0.45	(0.41, 0.51)	0.31	(0.28, 0.35)	0.36	(0.34, 0.39)
	U	221	(51, 1800)	114	(36, 578)	7	(3, 23)	35	(20, 88)
RFM									
saccade	α	0.19	(0.14, 0.25)	0.29	(0.25, 0.34)	0.29	(0.22, 0.32)	0.20	(0.18, 0.23)
	U	16	(3, 154)	26	(9, 126)	2200	(170, ∞)	14	(7, 38)
percept	α	0.33	(0.29, 0.38)	0.45	(0.41, 0.51)	0.27	(0.24, 0.31)	0.36	(0.34, 0.39)
	U	105	(31, 616)	100	(36, 487)	17	(6, 57)	55	(30, 148)
STS									
saccade	α	0.06	(0.01, 0.18)	0.13	(0.03, 0.23)	0.19	(0.10, 0.20)	0.13	(0.07, 0.19)
	U	18	(0, ∞)	56	(0, ∞)	∞	(28, ∞)	220	(13, ∞)
percept	α	0.15	(0.11, 0.19)	0.20	(0.17, 0.24)	0.24	(0.21, 0.28)	0.19	(0.17, 0.21)
	U	10	(2, 61)	9	(3, 39)	471	(87, 6800)	26	(13, 69)

[a] Each cell reports the maximum-likelihood value and, in parentheses, the 95% confidence interval.   The symbol ∞ represents an uncertainty value greater than 10,000.   The first three columns report individual fits for the three target letter tasks, and the fourth column reports a single simultaneous fit to all three target letter tasks.   See Figs. 2 and 3 for plots.
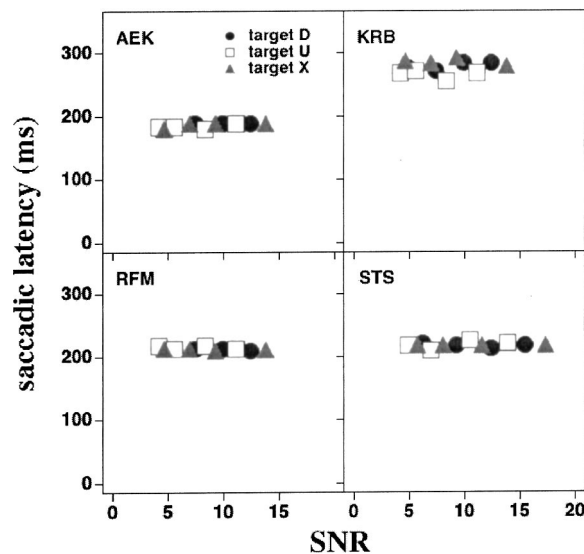

Fig. 5.   Median saccadic latency in experiment 1.   The error bars show standard errors and are smaller than the data points.

the same as those when we made separate fits for each target letter task: Saccadic α was significantly lower than perceptual α for all observers ($p < 0.05$), but saccadic U was lower than perceptual U for only observer RFM ($p < 0.01$).[24]

5.   *Matching Processing Times for Saccadic and Perceptual Decisions*

To compare saccadic and perceptual performance properly, it is important for the effective stimulus duration to be matched in the saccadic and perceptual tasks.   However, all observers' saccadic latencies turned out to be longer in the main experiment than in the practice ses-

sions that we used to determine the stimulus duration on FIX trials.   Figure 5 shows each observer's mean saccadic latency in each target letter task at each signal contrast.   Median saccadic latency on EM trials, across all letter tasks and signal contrasts, was 183 ms for observer AEK, 213 ms for RFM, and 217 ms for STS, and for these observers the FIX stimulus duration was 150 ms.   Median saccadic latency was 275 ms for observer KRB, and for this observer the FIX stimulus duration was 250 ms.   Standard errors of the medians were approximately ±2 ms.   We have assumed that the time available for saccadic processing is the saccadic latency minus 90 ms,[15] which means that in this experiment the effective stimulus duration was approximately 40 ms shorter for saccadic decisions than for perceptual decisions.   This discrepancy may have led us to underestimate the efficiency of saccadic responses relative to perceptual responses.

To address this problem, we calculated each observer's median saccadic latency over all EM trials, and we reran all FIX trials with the stimulus duration adjusted to reflect these more accurate measurements of saccadic latency.   We then recalculated each observer's relative efficiency, comparing saccadic performance on the original EM trials with perceptual performance in this second set of FIX trials, which we will call FIX2 trials when we need to distinguish them from the first set of FIX trials.   The revised stimulus duration was 83 ms for observer AEK, 167 ms for KRB, and 117 ms for RFM and STS.   The results of this follow-up experiment were practically identical to the results of the main experiment.   Mean relative efficiency, averaged across target letters and signal contrasts, was as follows: observer AEK, 16.9% ± 2.3%; KRB, 21.9% ± 1.9%; RFM, 21.3% ± 2.0%; and STS, 0.4% ± 0.4%.   Thus our results were not strongly biased by the error in our original estimates of saccadic latency.[25]

6. Speed–Accuracy Trade-Off

We also examined saccadic latencies to see whether the differences in saccadic accuracy across target letter tasks or signal contrasts might be due to differences in saccadic processing time, i.e., due to a speed–accuracy trade-off. Figure 5 shows that median latency was almost constant across target letters and signal contrasts, typically varying by only a few milliseconds. This impression was confirmed by within-observer ANCOVAs, which found no effect of saccadic accuracy (measured in terms of d') on median latency and found an effect of target letter on median latency for only observer KRB [$F(2, 8) = 11.70$, $p < 0.01$]. Thus the differences in saccadic accuracy were not due to a speed–accuracy trade-off.

7. Free-Viewing Perceptual Responses

Up to now, we have compared saccadic performance on EM trials with perceptual performance on FIX trials. Observers also made button-press responses on EM trials, and one would certainly expect these responses to be more accurate than the button-press responses on FIX trials, because on EM trials observers were free to make saccades and had a much longer viewing time. To quantify how much observers benefited from free-viewing conditions, we calculated the relative efficiency of perceptual responses on FIX trials with respect to perceptual responses on EM trials. As expected, relative efficiency was low. Observer AEK's mean relative efficiency was 15%, KRB's was 21%, RFM's was 17%, and STS's was 5%. Standard errors were approximately ±3%. Another way of making the same point is to note that absolute efficiency of free-viewing perceptual responses covered a range of 4%–21% and had a mean of 11% ± 4% over all observers, target letters, and SNRs. These values of absolute efficiency are much higher than those that we reported above for short-duration perceptual responses on FIX trials. Using similar methods, Beutter *et al.*[8] found that observers also benefited greatly from free-viewing conditions in visual search tasks involving disk detection and contrast discrimination.

C. Discussion

The main results of this experiment can be seen clearly in Figs. 2 and 3: Saccadic performance was better than chance but much worse than perceptual performance under matched conditions. All the subsequent analyses in Subsection 2.B are elaborations of this basic finding. A methodologically important elaboration, though, is our comparison of saccadic and perceptual performance in terms of relative efficiency. This comparison allowed us to quantify how well saccadic decisions made use of shape cues, compared with perceptual decisions. We found that, on average, the relative efficiency of saccadic responses compared with perceptual responses was 15%.

This result should be contrasted with Beutter *et al.*'s[8] finding that in visual search tasks involving disk detection and contrast discrimination, saccadic performance was similar to perceptual performance, with relative efficiency ranging from 80% to 100%. Taken together, our experiments and those of Beutter *et al.* show that saccadic and perceptual performance do not vary similarly from task to task: Saccadic performance compared with perceptual performance was differentially better at letter discrimination than at disk detection and contrast discrimination. This demonstrates that, in general, saccadic and perceptual decisions do not make similar use of stimulus information.

Similarly, our analysis of relative efficiency as a function of SNR showed that saccadic and perceptual performance did not depend in the same way on task difficulty: Not only was saccadic performance generally worse than perceptual performance, but it was especially poor at low SNRs, compared with perceptual performance. Again, this shows that the computations underlying saccadic and perceptual decisions are not the same.

3. EXPERIMENT 2: CONTRAST-RANDOMIZED LETTER DISCRIMINATION

Earlier studies have shown that saccades can be guided very efficiently by contrast differences between targets and distractors,[7,8] so to be certain that saccades were guided by shape cues in experiment 1, we must rule out the possibility that observers used simple contrast cues to locate the target letter. In experiment 1, the targets and the distractors had equal peak Weber contrasts, but there may have been useful contrast cues nevertheless, as there are several other ways of measuring perceptual salience that might be more appropriate than Weber contrast, such as contrast energy,[11] Michelson contrast,[12] or contrast in a narrow band of spatial frequencies.[13] Furthermore, for each of these contrast measures, we must decide whether to equate the contrast of the targets and the distractors as they appear on the monitor, or as they appear on the retina, or as they appear when adjusted by the observer's contrast sensitivity function, and so on. Finally, no matter which contrast cue we equate in the targets and the distractors, observers might be able to switch to a different contrast cue.

To avoid these difficulties, we carried out a control experiment in which we rendered all simple contrast cues uninformative by independently randomizing the contrasts of the target and distractor letters on every trial, so that even a statistically ideal decision maker who used only simple contrast cues would perform very poorly. If observers continued to perform well under these conditions, and in particular if they performed better than an ideal decision maker that used only simple contrast cues, then we could be certain that they were not using contrast differences between the target and the distractors to guide their saccades.

A. Methods

1. Participants

The two observers (KRB and RFM) who had the highest relative saccadic efficiency in experiment 1 participated.

2. Stimuli

The stimuli were the same as those in experiment 1, except that the contrasts of the target and the distractors were chosen from independent and identically distributed Gaussian distributions on every trial [Fig. 1(b)]. When the target was D, U, or X, the mean of the contrast distri-

bution was 20%, 16%, or 12%, and the standard deviation was 6.0%, 4.8%, or 3.6%, respectively. These mean contrast values are the highest contrasts used in the corresponding letter tasks in experiment 1. The standard deviations are 30% of the corresponding means and were chosen so that even model observers who made ideal use of simple contrast cues would achieve only low levels of performance (see Subsection 3.B.3 below).

3. Procedure

Each observer participated in two 1-h sessions. Each session consisted of six 100-trial blocks: one EM block and one FIX block for each of the three target letters (D, U, and X). The timing and the sequence of events in each trial were the same as in the EM and FIX2 trials of experiment 1, except that the stimulus was the contrast-randomized stimulus just described.

B. Results

1. Saccadic and Perceptual Decision Accuracy

Figure 6 plots saccadic and perceptual performance in terms of d' (left column) and also shows the relative efficiency of first saccadic decisions compared with perceptual decisions (right column). Even though the contrasts of the target and the distractors were independently randomized, both saccadic and perceptual performance were much better than chance, and the relative efficiency of saccades was greater than zero. Also, as in experiment 1, saccadic performance was worse than perceptual performance: Observer KRB's mean relative saccadic efficiency was 38.4% ± 3.5%, and RFM's was 49.0% ± 4.4%.

2. Matching Processing Time for Saccadic and Perceptual Decisions

Observer KRB's median saccadic latencies in the D, U, and X tasks were 271, 258, and 263 ms, respectively, and RFM's latencies were 213, 202, and 198 ms. Standard errors were approximately ±3 ms. The stimulus durations on FIX trials, which were 167 ms for observer KRB and 117 ms for RFM, were approximately 90 ms shorter than

Fig. 6. Saccadic performance, perceptual performance, and relative efficiency in experiment 2. The error bars show standard errors.

these saccadic latencies and so were well matched to observers' saccadic processing times.

3. Contrast Cues

To confirm that we succeeded in rendering simple contrast cues uninformative by randomizing the peak Weber contrast of the targets and the distractors, we evaluated the performance of five model observers who made statistically optimal decisions based on simple contrast cues. The model observers attempted to locate the target letter in stimuli exactly like those shown to the human observers. Because they used only simple contrast cues, these model observers performed much worse than ideal observers. The first model observer calculated the peak Weber contrast at each of the ten stimulus locations (i.e., the highest contrast of any single pixel inside each of the ten stimulus boxes), and the second observer calculated the peak Weber contrast at each location after filtering the stimulus by the contrast sensitivity function reported by Watson.[26] The third observer calculated the total contrast energy at each stimulus location, and the fourth observer calculated the total contrast energy at each location after filtering by the contrast sensitivity function. The fifth observer calculated the cross correlation of each stimulus location with a Gaussian blob centered in the stimulus box, which is probably the strategy that observers used to perform Beutter *et al.*'s contrast discrimination tasks.[8,27] We evaluated the fifth observer with a range of Gaussian blob sizes to see whether any size would produce good performance. Appendix A gives further details of the model observer calculations.

We found that the performance of the first four model observers was only slightly better than chance, never exceeding 15% correct ($d' = 0.3$) on any task, even though they made optimal use of simple contrast cues. The fifth model observer performed the target X task well when the Gaussian blob was small, achieving 96% correct ($d' = 3.6$) when the blob covered only the central part of the stimulus, where the middle of the target letter X had high contrast and the empty center of the distractor letter O had zero contrast. However, even this model observer performed the target D and target U tasks poorly, regardless of the Gaussian blob size, with performance never exceeding 22% correct ($d' = 0.6$). (No doubt this observer could also have performed the D and U tasks well with an intelligently placed and sized Gaussian blob, but this would just be a crude way of using shape information, not a simple contrast cue.) The human observers' saccadic and perceptual performance was always better than 34% correct ($d' = 1$), so they performed better than all five model observers in two of the three target letter tasks, and they therefore cannot have based their responses on only the simple contrast cues that the model observers used. This supports our conclusion that observers used shape cues to guide their saccades.
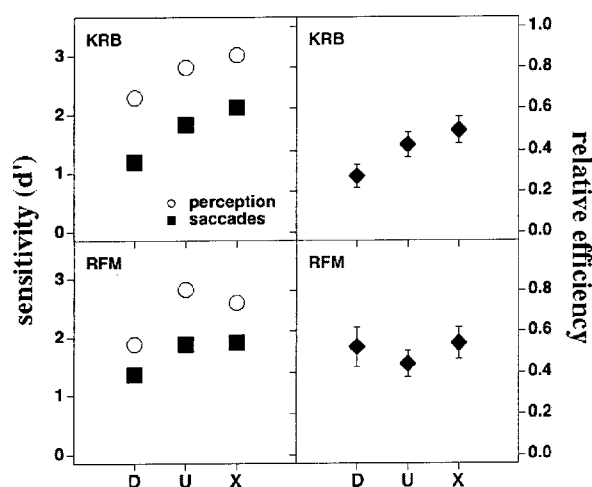
C. Discussion

These results show that the first saccade during visual search for a target letter is not random, even when contrast differences between the target and the distractors

are uninformative. This is an important control experiment, given how efficiently observers can use contrast cues to guide saccades.[7,8] In fact, shape and contrast cues have been confounded in every previous study that has investigated whether shape cues can guide saccades, to the best of our knowledge. To take just one example, Viviani and Swensson[3] found that when observers searched for a small star among small dots, the first saccade often went directly to the star. However, their stimuli did not equate the contrast energy of the star and the dots, so observers may have made saccades using only contrast energy cues and not shape cues. This problem is less severe when targets and distractors differ only by a rotation, e.g., the target "+" and the distractor "×" used by He and Kowler,[4] but even here small differences in perceived contrast due to the oblique effect[25] might contribute to saccadic performance. The present experiment shows that even when such cues are unreliable, first saccades are better at locating a target than one would expect by chance alone.

In fact, the relative efficiency of first saccades was even higher in this experiment than in experiment 1 ($p < 0.01$). In experiment 1, observer KRB's mean relative efficiency, averaged across the highest signal contrast in each target letter task, was $26.5\% \pm 2.2\%$, and observer RFM's was $32.2\% \pm 2.5\%$. (Recall that the highest signal contrast in each letter task of experiment 1 was the same as the mean of the contrast distribution in the corresponding letter task of this experiment, so this is the most relevant comparison.) In this experiment, KRB's mean relative efficiency was $38.4\% \pm 3.5\%$, and RFM's was $49.0\% \pm 4.4\%$. The differences in relative efficiency between the two experiments were due to differences in both perceptual and saccadic performance: For both observers in all three letter tasks, perceptual d' was lower on FIX trials of this experiment than on the FIX and FIX2 trials of experiment 1, and with the exception of observer RFM in the target U task, saccadic d' was higher on the EM trials of this experiment than on the EM trials of experiment 1.

It is understandable that perceptual performance should be worse in this experiment than in experiment 1, because here the signal was contrast randomized, so the task was intrinsically harder (i.e., even an ideal observer would perform worse in experiment 2). It is unclear why saccadic performance should be better in this task. It may be that both perceptual and saccadic performance improved with practice but that contrast randomization worsened perceptual performance more than saccadic performance. Contrast randomization would worsen perceptual performance more, for instance, if the perceptual template covered more of the target and distractor letters than the saccadic template did, because contrast randomization would then introduce more noise into the perceptual decision variable. The net effect of practice and a differential effect of contrast randomization could be a worsening of perceptual performance and an improvement of saccadic performance. This explanation is clearly speculative and is intended mainly to show that the observed pattern of results could be explained by simple properties of the saccadic and perceptual pattern recognition mechanisms, even if we are not in a position to test possible explanations with the results of the present experiment.

In any case, the surprisingly high relative efficiency of saccades actually supports our main conclusion more strongly, namely that first saccadic responses can be moderately efficient compared with perceptual responses, even when contrast cues are unreliable and responses must be based on shape differences between the target and the distractors.

4. EXPERIMENT 3: LETTER DETECTION

In the third experiment, we compared saccadic and perceptual performance in a task where observers searched for a target letter with no distractor letters. We did this for two reasons. First, as part of our plan of investigating whether saccadic and perceptual performance were affected similarly by a variety of task manipulations, we wanted to see whether saccadic and perceptual performance were affected similarly by whether a task required discrimination or detection of letters. Second, we wanted to confirm that relative saccadic efficiency was low in experiment 1 because the task required letter discrimination and not just because some peculiarity of our letter stimuli made them less detectable for the saccadic system than for the perceptual system; e.g., perhaps the spatial frequencies of the letters fell largely outside the range to which the saccadic system is sensitive. If observers achieved high relative saccadic efficiencies on a letter detection task, this would indicate that the saccadic system was sensitive to the letter stimuli and would show that the relative saccadic efficiency was low in experiment 1 specifically because the saccadic system could not make efficient use of shape differences between the letters to guide saccades.

A. Methods

1. Participants
The same four observers participated as in experiment 1.

2. Stimuli
The stimuli were the same as in experiment 1, except that the peak Weber contrast of the target was 7% for observers AEK, KRB, and RFM and 8% for STS, and nontarget locations did not contain distractor letters [Fig. 1(c)].

3. Procedure
Each observer participated in two 80-min sessions. Each session consisted of eight 100-trial blocks: one EM block and one FIX block for each of the four target letters (D, O, U, and X). The timing and the sequence of events in each trial were the same as those in the EM and FIX2 trials of experiment 1, except that the stimulus was the letter detection stimulus just described.

B. Results

1. Saccadic and Perceptual Decision Accuracy
Figure 7 plots saccadic and perceptual performance in each letter task in terms of d' (left column) and also
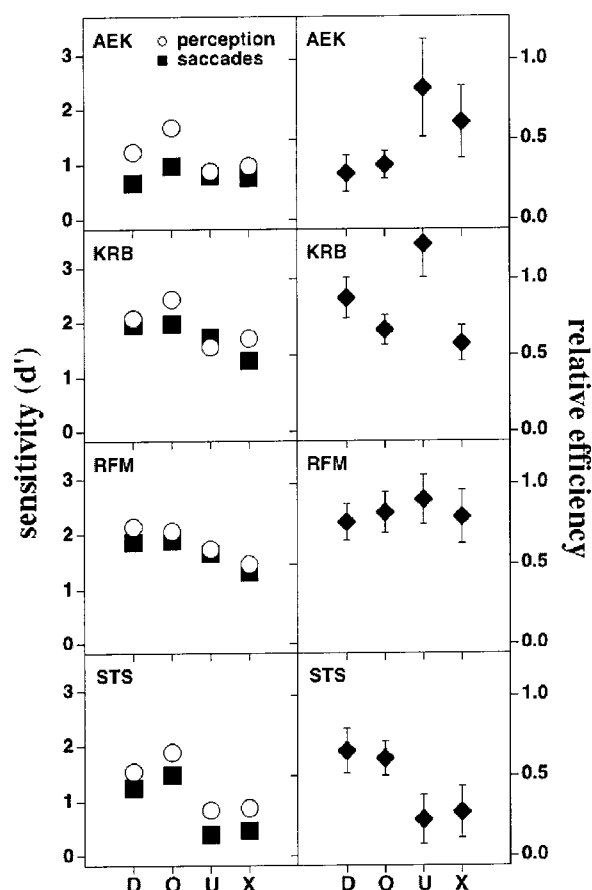
Fig. 7.   Saccadic performance, perceptual performance, and relative efficiency in experiment 3.   The error bars show standard errors.

shows the relative efficiency of saccadic responses compared with perceptual responses (right column).   The accuracy of the first saccade on EM trials was better than chance, though not as good as perceptual accuracy on FIX trials.   Mean relative saccadic efficiency, averaged across letter tasks, was as follows: observer AEK, 37.0% ± 6.4%; KRB, 73.1% ± 6.1%; RFM, 81.0% ± 6.8%; and STS, 48.5% ± 6.8%.   All observers had much higher mean relative efficiency in this experiment than in experiment 1 ($p < 0.01$ in two-tailed t tests).   Thus saccadic and perceptual performance did *not* vary similarly between detection and discrimination tasks: Saccadic performance compared with perceptual performance was differentially better at detection than at discrimination.

2.   Matching Processing Time for Saccadic and Perceptual Decisions

Median saccadic latency over all four letter tasks was 179 ms for observer AEK, 267 ms for KRB, 217 ms for RFM, and 217 ms for STS.   Standard errors were approximately ±2 ms.   These latencies were approximately 90 ms longer than the stimulus durations on FIX trials, so the saccadic and perceptual processing times were well matched.   Furthermore, the latencies were within ±8 ms of the latencies in the letter discrimination tasks of experiment 1, so, although the differences were statistically significant for some observers, they were not large.

C.   Discussion

The relative efficiency of saccadic responses compared with perceptual responses was much higher in this letter detection task than in the letter discrimination task of experiment 1, which is to say that saccadic accuracy was much closer to perceptual accuracy in this experiment. This result is similar to Beutter *et al.*'s[8] finding that relative saccadic efficiency was 80% for disk contrast discrimination and 100% for disk detection.   Both of these experiments show that saccadic responses are differentially better at detection than at discrimination, compared with perceptual responses.   This is further evidence that different computations underlie saccadic and perceptual responses.   Clearly, though, the difference was much greater in our experiments than in Beutter *et al.*'s, which suggests that the saccadic and perceptual systems make similar use of stimulus information in simple tasks such as disk detection and contrast discrimination and differ more strongly in how they use complex shape information.

Relative efficiency was lower in our letter detection tasks than in Beutter *et al.*'s disk detection tasks, but this is to be expected, given that relative efficiency was lower in our shape discrimination tasks than in Beutter *et al.*'s disk contrast discrimination tasks: If the saccadic system cannot use shape cues efficiently in letter discrimination tasks, then we should not expect it to use shape cues efficiently in letter detection tasks.   For instance, suppose that observers made saccadic and perceptual decisions by using a template-matching strategy.   If the perceptual template was better matched to the stimuli than the saccadic template was, then saccadic performance would be worse than perceptual performance in both discrimination and detection tasks.

Another difference between our results and those of Beutter *et al.* was that the relative efficiency of saccades was much higher in our letter detection tasks than in our letter discrimination tasks, whereas the relative efficiency of saccades was only slightly higher in Beutter *et al.*'s disk detection tasks than in their disk contrast discrimination tasks.   This suggests that the contrast sensitivity function of the saccadic system peaks at much lower frequencies than the contrast sensitivity function of the perceptual system.   To see why, consider the fact that the spatial-frequency spectrum of letters (which are ideal templates for letter detection) is low pass with a peak at the dc component, whereas the spectrum of letter difference images (which are ideal templates for letter discrimination, e.g., an image of the letter X minus an image of the letter O) is bandpass with little energy at the dc component. (We confirmed these generalizations with our letter stimuli.)   If the saccadic system has a more low-pass contrast sensitivity function than the perceptual system, then relative efficiency of saccades will be higher in letter detection tasks than in letter discrimination tasks, because in letter detection tasks the relevant stimulus information is concentrated at low spatial frequencies.   We found precisely this pattern of results in our letter search experiments.   Also, note that the ideal template is the same for disk detection and disk contrast discrimination (in both cases, it is a disk), so just from a consideration of the spatial-frequency selectivity of the saccadic and per-

ceptual systems, we would expect no difference in relative saccadic efficiency between these two tasks. In fact, Beutter *et al.* did find only a small difference in relative saccadic efficiency. The comparison of our results with Beutter *et al.*'s is crucial for this argument, because if Beutter *et al.* had found a large difference in relative efficiency between their disk detection and discrimination tasks, this would undercut any explanation of the difference that was based on differences in the spatial-frequency distribution of task-relevant information. Thus a comparison of our results and Beutter *et al.*'s suggests that the saccadic system may have a very low-pass contrast sensitivity function.

Finally, we can conclude that relative saccadic efficiency was low in experiment 1 at least partly because the task required letter discrimination and not just because the letter stimuli were less detectable for the saccadic system than for the perceptual system. With exactly the same letter stimuli, observers had much higher relative saccadic efficiencies in the letter detection task of this experiment than in the letter discrimination task of experiment 1.

5.   GENERAL DISCUSSION

A.   Do Shape Cues Guide Saccades?

The first question that we set out to answer was whether saccades are guided by shape differences between targets and distractors during visual search. We conclude that shape cues do guide saccades, but weakly. Experiment 1 showed that the first saccade during visual search for a target letter among distractor letters is not random but that its efficiency is low relative to that of perceptual responses under matched conditions. Experiment 2 showed that saccadic accuracy is better than chance even when contrast cues are virtually eliminated, indicating that saccadic performance in experiment 1 was not based on contrast differences between targets and distractors. Experiment 3 showed that differences between the letter discrimination performance of the saccadic and perceptual systems are not easily explained by differences in the ability of the saccadic and perceptual systems to detect letters.

Although we have shown that saccades are guided by shape cues, we still know little about precisely what *kind* of shape cues the saccadic system uses. For instance, if we regard the saccadic pattern recognition system as a template-matching mechanism, we cannot conclude that its templates in letter search tasks are matched to letter-like patterns. Even if the saccadic system could use only Gaussian blob templates, it could still discriminate between letters if it chose the size and the location of the blobs intelligently, e.g., in our search tasks, a Gaussian blob centered in each stimulus location can discriminate between a target X and a distractor O quite well. Of course, our results do not give us any strong reason to believe that the shape cues that the saccadic system uses are qualitatively *different* from the shape cues that the perceptual system uses, either. We merely mean to point out that the question as to what kind of shape cues the saccadic system can use is currently unresolved. Below (Subsection 5.E) we discuss a method that could answer this question.

Similarly, it is difficult to know how our results will generalize to other tasks. Does relative saccadic efficiency change as a function of target eccentricity, or target size, or type of shape cue that distinguishes targets from distractors? Because we do not yet know exactly what stimulus properties guide saccades, answers to these questions will have to await further investigations.

B.   Do Saccadic and Perceptual Decisions Make Similar Use of Stimulus Information?

Our second question was whether saccadic and perceptual performance are affected similarly by a variety of stimulus manipulations, which, if true, would suggest that they make similar use of stimulus information and may be based on the same neural mechanisms. It is worth emphasizing that the manipulations that affected intrinsic task difficulty had qualitatively similar effects on saccadic and perceptual performance: Both saccadic and perceptual performance were better at high signal contrasts, and both were better with more highly discriminable target–distractor pairs. However, we found that three stimulus manipulations had quantitatively different effects on saccadic and perceptual performance. First, the most striking difference was that the efficiency of saccadic responses relative to perceptual responses was much lower in our letter detection and discrimination tasks than in Beutter *et al.*'s[8] disk detection and contrast discrimination tasks. Second, we found that the efficiency of saccadic responses relative to perceptual responses was much lower in letter discrimination tasks than in letter detection tasks. Third, we found that the efficiency of saccadic responses relative to perceptual responses increased at higher SNRs. These findings do not *refute* the notion that saccadic and perceptual responses are largely based on the same neutral mechanisms. It could be, for instance, that the saccadic and perceptual performance are limited by the same perceptual mechanisms and that the observed behavioral differences are due to late differences in the two systems, e.g., differences in the perceptual and saccadic decision stages. We can conclude, however, that one simple and appealing theory—that, in all tasks, perceptual and saccadic judgments rely entirely on the same mechanisms and hence respond identically to a variety of stimulus manipulations—is not true. The question as to why saccadic performance suffers relative to perceptual performance in shape discrimination tasks compared with contrast discrimination tasks, in discrimination tasks compared with detection tasks, and at low SNRs compared with high SNRs remains to be answered.

C.   Relation to Oculomotor Physiology

Saccades are mediated by subcortical pathways starting with a direct retinal projection to the superior colliculus (SC)[28–30] and by cortical pathways starting with a retinal projection to the primary visual cortex (V1) via the lateral geniculate, but also including critical pathways through the frontal eye fields (FEF) and the lateral intraparietal (LIP) cortex.[31,32] V1, FEF, and LIP in turn access brainstem saccadic motor pathways via direct projections to the SC.[33] This complex picture suggests that saccadic targeting could reflect cortical sensory representations

shared with perception[34] or cortical representations independent of perception,[35] or could be driven unconsciously by subcortical sensory signals.[36] Of particular relevance to this study, the inferior temporal (IT) cortex, which contains higher-order visual areas that are thought to be responsible for shape perception, appears to have access to the saccadic system via a direct projection to the SC.[33] Furthermore, extrastriate visual area V4, a ventral visual area, which provides a major input to the IT cortex,[37] contains neurons whose responses appear to encode spatial information about local stimulus features (orientation) and are directly correlated with saccadic targeting.[38] Our finding that, during search, the saccadic system has some knowledge about target shape, independent of contrast, may reflect some access to the V4-to-IT shape-processing ventral cortical pathway, but the low relative efficiency of this knowledge with respect to perception also suggests that saccadic access to this pathway may not be as complete as perceptual access.

D.   Matching Saccadic and Perceptual Decision Times

We have taken care to match the effective stimulus durations for saccadic and perceptual decisions, but the two types of responses were recorded in different ways and so took different amounts of time: First saccades occurred 180–280 ms after stimulus onset, whereas the arrow-rotation procedure for perceptual responses took several seconds. This raises the possibility that perceptual decisions benefited from the extra decision time (even though the stimulus was followed by a high-contrast mask) and therefore had an advantage over saccadic decisions. However, we do not believe that this poses a serious problem for our conclusions. First, using the same methods, Beutter *et al.*[8] found saccadic performance to be almost as good as perceptual performance in contrast discrimination tasks, indicating that perceptual decisions did not benefit greatly from the extra decision time. Second, the values of relative saccadic efficiency that we measured for letter discrimination were *much* lower than those that Beutter *et al.* measured for contrast discrimination ($\sim15\%$ versus $\sim80\%$), so in order to affect our conclusion that saccadic decisions use shape information less efficiently than they use contrast information, there would have to be an enormous difference in how much perceptual decisions benefited from extra decision time in the two types of tasks. Nevertheless, this is a conceivable, if unlikely, alternative explanation, so in further studies it would be useful to measure the accuracy of speeded-response perceptual decisions over a large range of response latencies in order to establish how much perceptual decisions benefit from extra decision time.

A related issue is whether the relative efficiency of saccades depends on what sort of saccadic response strategy an observer adopts: Can observers choose whether to make their first saccades rapid but inaccurate, or delayed and accurate? We did look for correlations between saccadic latency and saccadic performance, and we found none. Furthermore, it is not necessarily the case that moderate changes in observers' strategies in this respect would change the relative efficiency of saccades, because we would adjust the stimulus duration for perceptual responses accordingly, and it is an empirical question as to

how this would change relative saccadic efficiency, if at all. Presumably, though, at very long latencies, saccadic and perceptual performance would be the same: If observers viewed the stimulus for several seconds while foveating the fixation cross and then made either a saccadic or a perceptual response, it is difficult to see why saccadic and perceptual accuracy would differ, apart from different rates of oculomotor or button-press errors. This limiting case seems to be a degenerate form of visual search, however, where saccadic responses have a very different function from their usual role of directing the high-resolution fovea at regions of interest in order to gather task-relevant information. In our experiments, we chose not to give observers any instructions on saccadic response strategies, in order to study natural performance in visual search tasks. It is an open question as to how flexible observers' strategies are in this respect, apart from the degenerate limiting case of very long fixations, which is presumably a strategy that most observers can follow, if so instructed. However, saccadic latencies were approximately the same in our letter discrimination tasks as those in Beutter *et al.*'s contrast discrimination tasks, so the differences in relative saccadic efficiency between these two studies were not simply due to differences in saccadic latency.

E.   Shape Cues for Targeting Saccades

To conclude, we will note a parallel between our results and those of Rajashekar *et al.*,[39] who measured classification images from the target locations of saccades during visual search in order to determine what stimulus features attracted saccades. Their observers searched for a target in a field of Gaussian noise, and their classification images showed the average noise contrast at each pixel in a small region surrounding the end points of the observers' saccades. Thus the classification images revealed what patterns in the noise tended to attract saccades.[40] The results were consistent with our conclusion that the saccadic system does use shape cues, but inefficiently. Rajashekar *et al.* found that during visual search for a disk, the saccadic classification image was a circular blob; during search for a dipole (i.e., a black horizontal bar above a white horizontal bar), the classification image was the central portion of the dipole; and during search for a triangle, it was again a circular blob, perhaps with one side slightly flattened to match one straight edge of the triangle. That is, saccadic classification images were well matched to simple targets such as disks, but they were not well matched to even slightly more complex targets such as dipoles or triangles. On the other hand, perceptual classification images are often well matched even to complex signals, such as Vernier patterns and letters.[41–43]

To compare saccadic and perceptual classification images rigorously, one would have to measure them under conditions where saccadic and perceptual stimuli are matched for eccentricity and stimulus duration,[23] and one would have to consider the possibility that eye-tracking noise and fixational jitter degrade the saccadic classification images compared with the perceptual classification images. However, the similarity between Rajashekar *et al.*'s results and ours is certainly suggestive. Our ex-

periments have shown that the saccadic system does use shape cues, but not as efficiently as the perceptual system does. Further experiments involving measurement of classification images[27] could elucidate how the saccadic and perceptual systems differ in their use of shape information.

APPENDIX A: MODEL OBSERVERS THAT USE SIMPLE CONTRAST CUES

The notion of a "simple contrast cue" is open-ended. In our experiments, the targets and the distractors were defined by a spatial distribution of contrast, so any observer who could discriminate between them used a contrast cue of some sort. However, there is a continuum of such cues. At one end of the continuum are peak Weber contrast and total contrast energy, which do not measure shape in any useful sense, and at the other end are cues such as cross correlation with a template that is matched to the shape difference between the target and the distractors, which do depend on the stimulus shape. An intermediate cue might be horizontal contrast energy. To see whether saccadic performance in experiment 2 could have been based on cues at the simple-contrast-cue end of the continuum, we examined five model observers who made optimal use of such cues.

On each trial, the model observers were shown stimuli exactly like those shown to the human observers in experiment 2. Each model observer calculated a simple contrast cue from each of the ten stimulus locations and made a statistically optimal decision as to which location contained the target, given the values of the contrast cue. The target had an equal probability of appearing at each location, and the observer's goal was to maximize the proportion of correct responses, so the ideal strategy was to calculate the likelihood that the target had appeared at each possible location and to choose the location with the greatest likelihood. If the probability density functions of the contrast cue values generated by the target and distractor locations are T and D, respectively, and if the contrast cue measurements on a particular trial are $s_1, \ldots, s_{10}$, then the likelihood that the target appeared at location i on that trial is

$$L_i = T(s_i) \prod_{j \neq i} D(s_j). \tag{A1}$$

Thus the ideal strategy is to calculate L_i at each of the ten locations and to choose the location with the largest value.

The contrast cues that the model observers used were (1) peak Weber contrast (i.e., the highest contrast of any individual pixel inside the boxes enclosing each stimulus location), (2) peak Weber contrast after filtering by the contrast sensitivity function reported by Watson,[26] (3) total contrast energy, defined as the integral of squared Weber contrast over the entire stimulus location, (4) total contrast energy after filtering by the contrast sensitivity function, and (5) cross correlation with a Gaussian blob centered in the stimulus location. We evaluated the fifth

observer with many Gaussian blob sizes, with the scale constant (i.e., the standard deviation) ranging from less than 1 pixel to much larger than the target and distractor stimuli. For the Gaussian blob observer, the density functions T and D were Gaussian distributions whose mean and variance can be calculated from both the cross correlation of the Gaussian blob with the target and distractor letters and the power of the external noise. For the four other observers, we estimated the density functions empirically by calculating the contrast cues from targets and distractors on 10^6 simulated trials and tabulating the relative frequency of a large number of closely spaced contrast cue values. For all model observers, we calculated a different target density function T for each target letter task.

Once we had calculated the target and distractor density functions, we evaluated each model observer's performance by simulating 1000 trials in each target letter task, with stimuli exactly like those in experiment 2, and having the observer make responses according to the maximum-likelihood rule (A1). As described in the results section of experiment 2 (Subsection 2.B), all model observers performed worse than human observers, indicating that human observers cannot have used only these simple contrast cues to guide their saccades.

REFERENCES AND NOTES

1. J. M. Findlay, "Saccade target selection during visual search," Vision Res. **37**, 617–631 (1997).
2. I. T. Hooge and C. J. Erkelens, "Peripheral vision and oculomotor control during visual search," Vision Res. **39**, 1567–1575 (1999).
3. P. Viviani and R. G. Swensson, "Saccadic eye movements to peripherally discriminated visual targets," J. Exp. Psychol. Hum. Percept. Perform. **8**, 113–126 (1982).
4. P. Y. He and E. Kowler, "The role of location probability in the programming of saccades: implications for 'center-of-gravity' tendencies," Vision Res. **29**, 1165–1181 (1989).
5. L. G. Williams, "The effects of target specification on objects fixated during visual search," Acta Psychol. **27**, 355–360 (1967).
6. G. J. Zelinsky, "Using eye saccades to assess the selectivity of search movements," Vision Res. **36**, 2177–2187 (1996).
7. M. P. Eckstein, B. R. Beutter, and L. S. Stone, "Quantifying the performance limits of human saccadic targeting during visual search," Perception **30**, 1389–1401 (2001).
8. B. R. Beutter, M. P. Eckstein, and L. S. Stone, "Saccadic and perceptual performance in visual search tasks. I. Contrast detection and discrimination," J. Opt. Soc. Am. A **20**, 1341–1355 (2003).

9. D. M. Green and J. A. Swets, *Signal Detection Theory and Psychophysics* (Krieger, Huntington, N.Y., 1974).
10. W. S. Geisler, "Sequential ideal-observer analysis of visual discriminations," Psychol. Rev. **96**, 267–314 (1989).
11. H. Kukkonen, J. Rovamo, K. Tiippana, and R. Nasanen, "Michelson contrast, RMS contrast and energy of various spatial stimuli at threshold," Vision Res. **33**, 1431–1436 (1993).
12. P. Whittle, "Increments and decrements: luminance discrimination," Vision Res. **26**, 1677–1691 (1986).
13. D. J. Tolhurst and Y. Tadmor, "Band-limited contrast in natural images explains the detectability of changes in the amplitude spectra," Vision Res. **37**, 3203–3215 (1997).
14. B. R. Beutter and L. S. Stone, "Human motion perception and smooth eye movements show similar directional biases for elongated apertures," Vision Res. **38**, 1273–1286 (1998).
15. W. Becker and R. Jurgens, "An analysis of the saccadic system by means of double step stimuli," Vision Res. **19**, 967–983 (1979).
16. Oculomotor error in directing saccades almost certainly had little effect on saccadic accuracy, because there was a $360 \deg \div 10 = 36 \deg$ range corresponding to each stimulus location.   Using identical methods, Beutter *et al.*[8] recorded saccadic responses approaching 100% correct.
17. W. W. Peterson, T. G. Birdsall, and W. C. Fox, "The theory of signal detectability," IRE Trans. Inf. Theory **4**, 171–212 (1954).
18. In an *M*-alternative localization task, the ideal observer's strategy is to cross-correlate the stimulus at each of the *M* possible target locations with a template that is the difference image between the target and the distractor and to choose the location with the largest cross correlation.   See Ref. 8 for details.
19. See Ref. 9, Appendix 1, for a description of how to calculate d' in an *M*-alternative forced-choice task.
20. J. A. Solomon and D. G. Pelli, "The visual filter mediating letter identification," Nature (London) **369**, 395–397 (1994).
21. J. R. Taylor, *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements* (University Science, Mill Valley, Calif., 1982).
22. M. P. Eckstein, A. J. Ahumada, Jr., and A. B. Watson, "Visual signal detection in structured backgrounds. II. Effects of contrast gain control, background variations, and white noise," J. Opt. Soc. Am. A **14**, 2406–2419 (1997).
23. B. Efron and R. Tibshirani, *An Introduction to the Bootstrap* (Chapman & Hall, New York, 1993).
24. For all observers, the uncertainty parameters of the pooled oculometric and psychometric functions were significantly greater than zero ($p < 0.01$).   Beutter *et al.*[8] found that in disk contrast discrimination tasks, uncertainty was near zero for both saccadic and perceptual responses.   This difference is probably due to the fact that Beutter *et al.*'s discrimination task had a contrast pedestal, whereas ours did not.   That is, at low SNRs in our task, target and distractor letters were shown at contrasts that were near their detection threshold.   Low-contrast viewing conditions tend to increase uncertainty (see Ref. 22).
25. D. G. Pelli, C. W. Burns, B. Farrell, and D. C. Moore, "Identifying letters," Vision Res. (in press).
26. A. B. Watson, "Visual detection of spatial contrast patterns: evaluation of five simple models," Opt. Express **6**, 12–33 (2000).
27. M. P. Eckstein and S. S. Shimozaki, "Classification images for saccadic targeting and perceptual decisions during search," Perception **32** (supplement), 10 (2002).
28. R. H. Wurtz and J. E. Albano, "Visual-motor function of the primate superior colliculus," Annu. Rev. Neurosci. **3**, 189–226 (1980).
29. A. F. Fuchs, C. R. Kaneko, and C. A. Scudder, "Brainstem control of saccadic eye movements," Annu. Rev. Neurosci. **8**, 307–337 (1985).
30. D. L. Sparks, "The brainstem control of saccadic eye movements," Nature Rev. Neurosci. **3**, 952–964 (2002).
31. P. H. Schiller and E. J. Tehovnik, "Look and see: how the brain moves your eyes about," Prog. Brain Res. **134**, 127–142 (2001).
32. J. D. Schall, "The neural selection and control of saccades by the frontal eye field," Philos. Trans. R. Soc. London Ser. B **357**, 1073–1082 (2002).
33. W. Fries, "Cortical projections to the superior colliculus in the macaque monkey: a retrograde study using horseradish peroxidase," J. Comp. Neurol. **230**, 55–76 (1984).
34. R. J. Krauzlis and L. S. Stone, "Tracking with the mind's eye," Trends Neurosci. **22**, 544–550 (1999).
35. M. A. Goodale and A. D. Milner, "Separate visual pathways for perception and action," Trends Neurosci. **15**, 20–25 (1992).
36. J. Theeuwes, A. F. Kramer, S. Hahn, and D. E. Irwin, "Our eyes do not always go where we want them to go: capture of the eyes by new objects," Psycholo. Sci. **9**, 379–385 (1998).
37. R. Desimone, J. Fleming, and C. G. Gross, "Prestriate afferents to inferior temporal cortex: an HRP study," Brain Res. **184**, 41–55 (1980).
38. T. Moore, "Shape representations and visual guidance of saccadic eye movements," Science **285**, 1914–1917 (1999).
39. U. Rajashekar, L. K. Cormak, and A. C. Bovik, "Visual search: structure from noise," presented at the Symposium on Eye Tracking Research & Application 2002, New Orleans, La., March 25–27, 2002.
40. M. P. Eckstein and A. J. Ahumada, Jr., "Classification images: a tool to analyze visual strategies," J. Vision **2**, 1x (2002).
41. A. Ahumada, Jr., "Perceptual classification images from Vernier acuity masked by noise," Perception **26** (supplement), 18 (1996).
42. J. M. Gold, R. F. Murray, P. J. Bennett, and A. B. Sekuler, "Deriving behavioural receptive fields for visually completed contours," Curr. Biol. **10**, 663–666 (2000).
43. A. B. Watson and R. Rosenholtz, "A Rorschach test for visual classification strategies," Invest. Ophthalmol. Visual Sci. **38**, S1 (1997).